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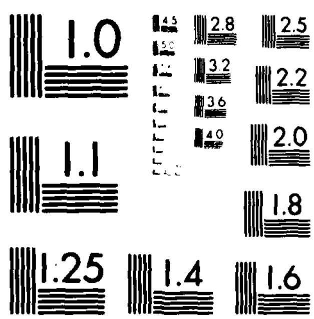

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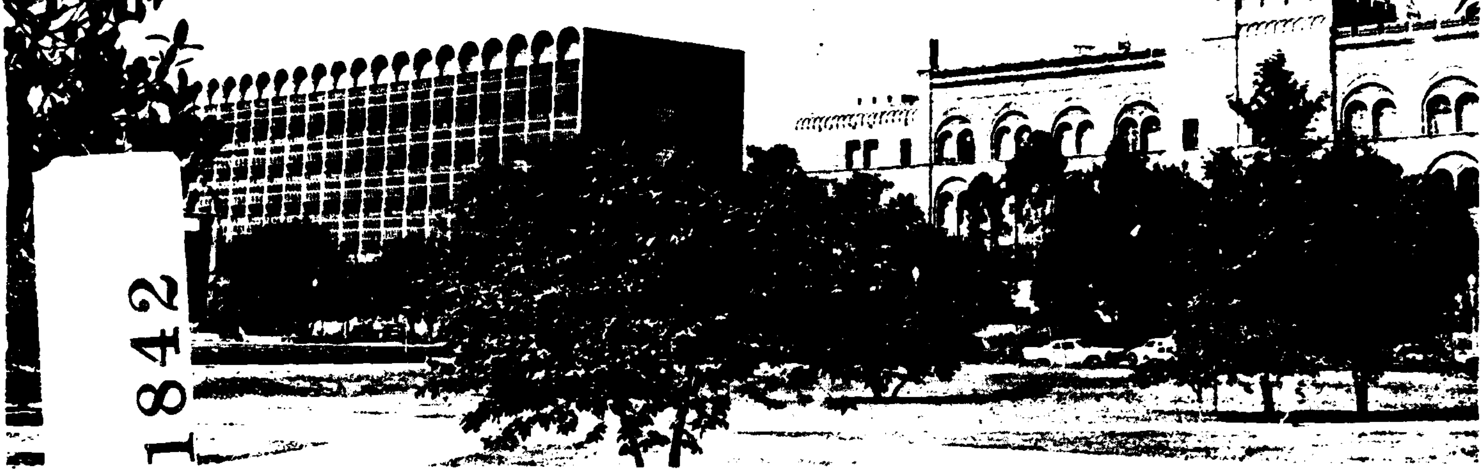

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INTERIM SUMMARY REPORT

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PROPAGATION OF SOUND IN MATTER

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March 1982

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The following Interim Summary Report covers the period October 1, 1968 to the present February 1, 1982, during which period research was conducted under Task Orders N00014-67-A-0111-0019, N00014-69-A-0200-4014 and N00014-75-C-0246. There exists a final report covering research work performed before this period under Task Order NONR 233(48) which is available on request. This contains brief Technical Descriptions of Research Completed numbered 1 to 27. (It is for this reason that the first item in this report is numbered 28.)

LIST OF THOSE WHO RECEIVED SUPPORT ON ONR CONTRACTS FROM 10/1/68-2/1/82 AND OBTAINED Ph.D. DEGREE IN PHYSICS, INCLUDING THEIR PRESENT PROFESSIONAL POSITIONS.

1. Imai, James S., Professor of Physics, California State University, Dominquez Hills, CA.

2. Kriss, Michael A., Laboratory Head and Research Physicist, Image Processing Laboratory, Eastman Kodak Company, Rochester, NY.

3. Fraser, James C., Research Physicist, Defense Advanced Research Projects Agency, Arlington, VA.

4. Scott, Stephen A., Went to dental school after receiving the Ph.D. and received the medical degree D.D.S.

5. Williams, Richard D., Research Physicist, The Optical Sciences Company, Placentia, CA.

6. Wang, Taylor G., Research Scientist, Jet Propulsion Laboratory, Pasadena, CA.

7. Commins, Daniel E., He established and runs the company-Commins bbm, Acoustical Consultants, Paris, France.

8. Kojima, Haruo, Associate Professor of Physics, Rutgers University, New Brunswick, NJ.

9. Telschow, Kenneth L., Associate Professor of Physics, Southern Illinois University, Carbondale, IL.

10. Scholtz, John H., Associate Research Scientist, Lockheed (Space Systems Division) Sunnyvale, CA.

11. Heiserman, Joseph E., IBM Fellowship and Postdoc at Stanford University for five years, now attending Stanford Medical School and also continuing experiments on ultrasonic-cryogenic scanning microscopes at Stanford.

12. Garrett, Steven L., Miller Institute Fellow, University of California at Berkeley; recently appointed Assistant Professor of Physics at the Naval Postgraduate School, Monterey, CA.

13. Talaghany, Roset Khosropour., returned to Iran after receiving Ph.D., future career positions and whereabouts uncertain.

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1. Imai, James S., Ultrasonic Attenuation in Liquid Helium at 1 GHz; Technical Report No. 28, April 1969.

2. Kriss, Michael A., Size Effects in Liquid Helium II as Measured by Fourth Sound and The Attenuation of Fourth Sound; Technical Report No. 29, June 1969.

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23. Ultrasonic Attenuation in Liquid Helium at 1 GHz

The ultrasonic attenuation in liquid helium at 1 GHz has been measured from about 1.1 to 4.2°K. The experiment gives a direct measurement of the absolute attenuation over the entire temperature range. The results are described in terms of three regions: a classical normal fluid region above 2.3°K, a critical region near the lambda transition, and a superfluid region below 2.0°K.

In the normal fluid region, the attenuation is due to classical shear viscosity and thermal conductivity, and is described by the Stokes-Kirchhoff equation. The results give good agreement, except for a gradually increasing surplus as T approaches the lambda transition, when compared with the theoretical Stokes-Kirchhoff attenuation curve.

In the critical region, the results are shown to differ in a fundamental way from those found at lower frequencies. The Landau-Khalatnikov order parameter relaxation mechanism is shown to contribute insignificantly to the attenuation in this region. In addition to the absolute attenuation measurements, the relative attenuation was measured in this region by a continuous drift in temperature. These measurements, when combined with the absolute attenuation, show a very large non-singular peak of about 2000 cm^{-1} centered at or very nearly at the lambda transition. The slopes of the attenuation peak, when fitted to a power law of the form $\alpha = \frac{A}{|T_\lambda - T|^n}$, give $A = 2.4 \times 10^2 (°K)^n/cm$, $\bar{n} = 0.41$ for $T > T_\lambda$, and $A = 1.5 \times 10^2 (°K)^n/cm$, $\bar{n} = 0.52$ for $T < T_\lambda$. Although recent theoretical treatments cite exponents for the power law ranging from 1/3 to 1, they contain an assumption about the convergence of the specific heat, C_p, to an asymptotic value which is not valid over the temperature region for which the critical behavior of the attenuation was determined. A comparison of the measurements with these theoretical results would thus be improper.

In the superfluid region, the attenuation measurements show the local maximum at 1.5°K which separates the hydrodynamic from the collisionless regime. The results are shown to be in agreement with the elementary excitation relaxation theory of Khalatnikov and Chernikova. They differ at lower temperatures from the results obtained from Brillouin scattering measurements.

This is the doctoral research work of James S. Imai. See Technical Report #28 and publication #'s 5 and 10.

29. Size Effects in Liquid Helium II as Measured by Fourth Sound and The Attenuation of Fourth Sound

Previous fourth sound (pressure-density waves in the superfluid component of He II) measurements in tightly packed powders revealed a systematic lowering of the superfluid density and superfluid onset temperature, T_o, below their bulk values. It was found that the lower T_o, the lower the value of the superfluid density at all temperatures. The resulting superfluid density versus temperature curves were found to form a family of curves whose characteristic parameter is T_o.

This thesis presents a systematic study of fourth sound measurements in resonators packed with fine powders ranging in diameter from 90 Å to 5μ and under packing pressures up to 45,000 psi. Superfluid onset temperatures from T_λ to 1.79°K are observed. The lowering of the superfluid density and superfluid onset temperature is found to be in good agreement with theoretical predictions based on size effects in He II, when pore size distributions of the packed powders are taken into consideration. Information on the pore size distributions is obtained from adsorption and desorption isotherms on the packed powders. The pore size distributions and measured values of T_0 indicate the presence of a strong interaction between adjacent pores near T_0.

Additional verification of an empirical acoustical index of refraction, n, due to multiple scattering in the packed powders is presented. The empirical value $n = (2-P)^{\frac{1}{2}}$, where P is the porosity of the packed powder, is compared to theoretical results and is found to be in disagreement with them.

The attenuation of fourth sound, as reflected in the quality factor, Q, of the resonances, is measured. The experimental results are compared with theoretical values of Q based on the imperfect locking of the normal fluid in the packed powders. The results show good agreement with theory for temperatures above 1.6°K, but the measured values of the Q fall below theoretical values below 1.6°K.

Measurements of the superfluid density near T_λ in a resonator free of size effects show $\rho_s/\rho \sim (T_\lambda - T)^{2/3}$ which is in excellent agreement with previous measurements and results based on the scaling laws.

This is the doctoral research work of Michael A. Kriss. See Technical Report #29 and publication #16.

30. Third Sound in Unsaturated Films of Superfluid Helium

The velocity of third sound in unsaturated films of superfluid helium has been measured at several temperatures between 1.12°K and 2.05°K. Helium films from 4 to over 100 atomic layers were adsorbed on glass substrates. The third sound waves were generated thermally. They were detected by sensing the very small temperature oscillations which accompany the hydrodynamic wave. The velocity was measured by the time of flight of sine wave pulses whose frequency ranged from 500 Hz to 5 KHz. The velocity was found to be less than that predicted by Atkins' hydrodynamic theory of third sound in saturated helium films which is based on the thermodynamic properties of the bulk liquid. Atkins' equations have been modified to take into account a variation of the thermodynamic properties of the film with thickness. An analysis of the velocity data has yielded the average superfluid density as a function of film thickness. Reduction of the superfluid fraction has been compared to the Ginzburg-Pitaevskii theory of superfluidity and a quantity which can yield values of the characteristic healing length of the theory has been determined from the data. The presence of a solid or normal fluid layer has been taken into account. If the assumption is made that there is a solid monatomic layer of helium at the substrate and that the superfluid order parameter vanishes, both at the solid layer and at the free surface of the film, then the healing lengths obtained from the data are given by

$2.9 \times 10^{-9}\ T/\rho_s$ (c.g.s.). The third sound signal was found to disappear when the velocity was near or at maximum. This disappearance has been interpreted as due to the loss of the superfluid properties of the film. The thickness at which this occurs is a function of temperature and agrees with the thickness for the onset of superflow determined by other mass-flow and heat-flow experiments. There is no evidence from independent experiments for a latent heat as large as would be implied by the rapid drop of the superfluid density to zero, inferred from the large sound velocity near onset. This has lead to the conclusion that the superfluid fraction is finite at onset. Its value at onset has been determined for the first time by these measurements to be a constant equal to about 3/8. The onset has been discussed in terms of a fluctuation theory developed by Revzen which predicts a temperature independent nonzero superfluid fraction at the onset of superflow. The Ginzburg-Pitaevskii theory does not predict this behavior. Preliminary measurements of the attenuation of third sound gives values in reasonable agreement with the attenuation predicted by a theory recently developed by Bergman. The attenuation was observed to rise sharply as the onset was approached. This suggests that there may be an additional mechanism for attenuation associated with fluctuations. No inconsistency has resulted from the application of a hydrodynamic theory to films as thin as 4 atomic layers.

This is the doctoral research work of James C. Fraser. See Technical Report #30 and publication #'s 4 and 15.

31. A Specific Heat and Fourth Sound Measurement of Size Effects in Liquid Helium

An experimental and theoretical investigation of liquid helium confined to the small pores of highly compressed powders was made in order to investigate size effects in liquid helium. The specific heat measurements show that the bulk specific heat singularity is replaced by a flattened peak that is shifted towards lower temperatures with decreasing pore size. The theory of second order phase transitions was used to calculate the specific heat of liquid helium in finite systems. The superflow onset temperature and ρ_s/ρ were determined from fourth sound measurements in the same powders in which specific heat measurements were made. The onset temperature and the temperature of the specific heat peak are equal within experimental error.

This is the doctoral research work of Stephen A. Scott. See Technical Report #31 and publication #33.

32. Experimental Study of the Lambda Transition of Liquid Helium Using First Sound Attenuation

The temperature and frequency dependence of the ultrasonic attenuation of first sound in liquid helium has been measured, using a pulse echo technique, in the ± 10 millidegree neighborhood of the lambda transition. Microdegree temperature resolution is obtained by using slow temperature drifts (approximately 1×10^{-7} °K sec^{-1} near T_λ). Measurements were made at four frequencies: 600 KHz, 1 MHz, 1.75 MHz, and 3.17 MHz. The measured attenuation remains finite, is asymmetric about the transition, and exhibits a maximum on the low temperature side. The position and magnitude of this maximum was measured in the range 16.8 KHz to 300 KHz using a resonant technique. At a frequency ω, the maximum attenuation is shown to occur at a temperature, T, below T_λ such that $\omega\varepsilon^{-1}$ = const., where $\varepsilon = |T_\lambda - T|$. The absorption of sound near T_λ can be interpreted as being due to two phenomena: (1) a relaxation process described by Pokrovskii and Khalatnikov occurring only below T_λ, and having a relaxation time of $\tau = \xi/C_2$ where C_2 is the velocity of second sound and ξ is a coherence length of magnitude 1.36×10^{-8} $(T_\lambda - T)^{-2/3}$ cm; (2) a critical attenuation which is non-singular and symmetric about T_λ due to inherent fluctuations in the order parameter.

This is the doctoral research work of Richard D. Williams. See Technical Report #32 and publication #'s 18 and 19.

33. Attenuation of Third Sound in Liquid Helium

and

The Stability of Multiply Quantized Persistent Circulations of a Thin Helium Film in the Landau Region

The attenuation coefficiency has been measured by generating a third sound in a He II film coating a cylinder and observing the decay of pulses which propagate in both directions around the axis of the cylinder. The observed attenuations can be divided into three regions:

(1) Thick film region: The attenuation here is 2 to 3 orders of magnitude greater than that given by Bergman (or by Atkins). There is evidence that, in part of this region, the thickness dependence is similar to that of the theoretical result, although this is not firm.

(2) Intermediate film thickness region: This is the region where third sound signals suffer minimum attenuation and the signal-to-noise ratio is best. This also includes the region where the experimental data are best fitted by Bergman's theory.

(3) Thin film (critical thickness region): As the film thins and approaches the onset thickness, the attenuation was found to be exponentially dependent on the film thickness and to increasingly exceed that of the Bergman theory. Revzen has predicted a similar dependence for the mobility of a thin superfluid film. The temperature dependence of the attenuation excess above that of the Bergman theory deviates significantly from that predicted for the mobility.

The measurement of α as a function of frequency in the intermediate film thickness region has been measured and found to vary with the square root of the frequency, in agreeement with the Bergman theory.

The stability of multiply quantized persistent circulations was investigated by measuring the relative velocity of two third-sound waves thermally generated from two parallell aluminum strips and detected by a superconductor strip midway between them.

The experimental results indicated that, when the cylinder was brought into rotation from rest at $T < T_\lambda$, the superfluid velocity always followed the substrate velocity and returned to rest as the substrate was stopped.

Further, when the cylinder was in rotation at $T > T_\lambda$, then cooled, while rotating, to a temperature lower than T_λ, the superfluid velocity was found to be identical with that of the substrate.

We conclude that persistent currents with high quantum numbers are unstable in times of the order of that of the experiment, namely 1/60 sec. The accuracy of the experiment does not allow us to reach this conclusion for circulation quantum numbers less than 1000.

This is the doctoral research work of Taylor G. Wang. See Technical Report #33 and publication #'s 30 and 34.

34. Hypersonic Attenuation in the Vicinity of the Superfluid Transition of Liquid Helium

The attenuation of first sound waves has been measured in liquid helium at a frequency of 1 GHz. Absolute measurements were performed with a variable path interferometer for temperatures extending from 1.1°K to 4.2°K. The results confirm those obtained earlier by the same method and those obtained from the Brillouin spectrum of scattered light. They can be described in terms of three regions: a) the normal fluid region above 2.3°K where the attenuation is attributed to the classical losses associated with viscosity and thermal conduction; b) the critical region between 2.0°K and 2.3°K, where the attenuation has a sharp peak occurring near T_λ; c) the superfluid region where the attenuation shows a broad maximum centered at 1.5°K and which is in agreement with the Khalatnikov-Chernikova theory. When the 1 GHz results are compared with the Brillouin scattering results, which vary in frequency from 556 MHz to 768 MHz, it is found that the attenuation scales as ω^2 over the whole temperature range with the possible exception of the data below 1.5°K and in the immediate vicinity of T_λ.

In the critical region, extending from 2.0°K to 2.3°K, more accurate attenuation measurements were performed with a fixed path interferometer. The helium sample was isolated from the helium bath and its temperature was allowed to drift as slowly as 3×10^{-6} °K $\sec^{-1}$.

The attenuation exhibits a sharp maximum in the region of the lambda transition; the largest value is about 2500 cm^{-1} and occurs at a temperature $T_\lambda - T_p = 3.26 \pm 0.20$ millidegrees, which was found to be independent of the power of the input signal.

After subtracting the classical attenuation due to viscous and thermal losses, the temperature dependence has been determined on both sides of the peak by fitting a power law of the form

$$\alpha = a/|T_p - T|^n$$

if the immediate vicinity of the maximum is excluded.

For $T > T_\lambda$, $\bar{n} = 0.49 \pm 0.06$ and $\bar{a} = 232\ (°K)^n/cm$.

For $T < T_\lambda$, $\bar{n} = 0.51 \pm 0.05$ and $\bar{a} = 152\ (°K)^n/cm$.

The contribution of the Landau-Khalatnikov relaxation mechanism at a frequency of 1 GHz is a peak, centered 94 m°K below T_λ, of only about 180 cm^{-1}; therefore the present results cannot be explained by such a process. The other existing theories have been surveyed and no satisfactory explanation of the sharp attenuation peak has been found.

This is the doctoral research work of Daniel E. Commins. See Technical Report #34 and publication #31.

35. Investigation of Persistent Current States in Rotating Superfluid Helium Contained in Superleak Using Doppler-Shifted Fourth Sound

Fourth sound techniques were extensively developed into a powerful tool for investigating persistent current states in rotating superfluid helium contained in a superleak. Unique features of these techniques are : (1) persistent superfluid component velocity is directly determined by the Doppler-shifted splitting of a fourth sound resonant mode in an annular cavity; (2) the superfluid component density is determined simultaneously and independently by measuring the velocity of fourth sound; (3) persistent current states are observed from a rotating frame. The fourth sound techniques allow us to observe persistent current states which are otherwise inaccessible in a stationary measurement. As a consequence we show that every phenomenon observed in rotating locked superfluid helium (Bose superfluid) has an analogous counterpart in an irreversible type-II superconductor (Fermi superfluid). On the basis of these studies we make the following statements regarding the nature of superfluid helium persistent current states. (1) An extensive Landau region ($\nabla \times \vec{v}_s = 0$ everywhere), where vortices are excluded, is directly observed below a rather large critical angular velocity, ω_{c_1}. This is similar to Meissner region in the superconductors. (2) The upper critical angular velocity, ω_{c_2} (analogous to H_{c_2}), where the superfluidity vanishes, is unattainably large at a low temperature. (3) Between the two critical angular velocities the relative angular velocity between the superfluid and normal fluid components, $\omega_n - \omega_s$, reaches a maximum saturated critical value, ω_σ. (4) Once the critical angular velocity ω_{c_1} is exceeded the superfluid component angular velocity exhibits a strong hysteresis behavior, which is related to the entrance of vortices. There is evidence that vortices of opposite sign to that of preexisting ones are created. Past history is important. (5) If the helium filled superleak is cooled through T_λ to some lower temperature, then so long as the superleak is kept rotating at its initial velocity, ω_i, the superfluid component will also have that velocity ω_i. If the angular velocity is subsequently decreased a circulation-free potential flow and a vortex flow are induced which lower the superfluid component angular velocity. (6) The critical angular velocity, ω_{c_1}, and the saturated critical angular velocity, ω_σ, were measured as a function of temperature. Below about 1.85K ω_{c_1} is independent of temperature and it decreases rapidly toward zero as T_λ is approached. Above 1.30K ω_σ decreases monotonically toward zero as T_λ is approached. (7) Reppy and his coworkers have shown that saturated persistent currents decay logarithmically with time just as corresponding superconducting currents. We extended these measurements to include five decades in time (1 to 10^5 sec) and previously unobserved decay of persistent currents whose velocity is less than the saturated value. All such initially unsaturated currents decay at a logarithmic rate determined by the initial, rather than instantaneous, value of the current. (8) The first observation of the superfluid component density <u>reduction</u> as a function of the square of the relative velocity between the two components, $(\vec{v}_n - \vec{v}_s)^2$, was made. The dependence on $(\vec{v}_n - \vec{v}_s)^2$ is very complicated and not yet understood. Experimental values are compared with theoretical predictions.

This is the doctoral research work of Haruo Kojima. See Technical Report #35 and publication #'s 9, 21, 24, 29, 32, and 44.

36. *Investigation of the Thickness and Critical Velocity of a Moving Unsaturated Superfluid Film Using Doppler Shifted Third Sound*

The velocity of third sound waves on a moving unsaturated superfluid film has been measured by the time of flight technique. The film was propelled by a heater placed at one end of a glass substrate. Two smoothly connected cylindrical glass sections, with diameters in a ratio of approximately 4:1, formed the substrate and allowed simultaneous measurements at two different film flow velocities. The Doppler shift was determined to be $\frac{C_3^+ - C_3^-}{2} = \frac{\langle\rho_s\rangle}{\rho} V_s$ where $C_3^{\pm}$ is the velocity of the wave parallel and antiparallel to the film flow velocity V_s and $\frac{\langle\rho_s\rangle}{\rho}$ is the reduced superfluid fraction in the unsaturated film.

The thickness of the moving film was probed by the average of the two Doppler shifted velocities. To within experimental precision, no changes in the average velocity with the film flow velocity were observed. The thickness, therefore, is constant for the moving unsaturated film in agreement with previous experiments done on saturated films. This result presents a fundamental problem to the interpretation of the theory of liquid helium. Several possible resolutions to this paradoxical behavior are presented.

The critical flow velocity was measured by the abrupt change in the Doppler shift as the film was accelerated by increasing the heater power. This experiment measures the flow velocity more directly than previous experiments through the Doppler shift. The critical point was always very distinct in contrast to the behavior of temperature gradients within the film. At all temperatures investigated, the critical velocity rises rapidly from zero at the onset thickness to a maximum value and then decreases more gently as the thickness of the film increases. The maximum values are typically 100-200 cm/sec and increase with decreasing temperature. Qualitative agreement is observed between critical velocities reported here and a previous experiment with Doppler shift measurements on saturated films.

This is the doctoral research work of Kenneth L. Telschow. See Technical Report #36 and publication #'s 38 and 39.

37. Third Sound Velocity and Attenuation Below 1.2 Degrees Kelvin

The velocity of third sound on glass and CaF_2 substrates and at a variety of film thicknesses has been measured using a He_3 cryostat from temperatures of 1.2K down to 0.5K. Then with a dilution refrigerator the results on glass were extended to 0.1K. The third sound was generated and detected thermally in the usual manner, and the velocity was determined by measuring the time of flight of a pulse. Film thicknesses are found by measuring the chemical potential of the film at 1.5K. Thickness measurements depend on the van der Waals constants between helium and the substrates, and now as a result of recent experimental work by Anderson and Sabisky, great confidence can be placed in the knwoledge of these constants. A thickness is then held constant with respect to changes in temperature by employing a powder film reservoir with a large surface area.

The velocity measurements are used to determine the depleted superfluid fraction in the helium film and establish a thickness independent length D over which there is effectively zero superfluidity. The results of this experiment are very harmonious with older higher temperature third sound results and these, in turn, when evaluated with the correct van der Waals constant, are in excellent agreement with other similar experiments.

Third sound has now been observed in films as thin as 2.1 atomic layers, and hence indicates the existence of superfluidity in two dimensional systems. This is particularly true if one accepts the very reasonable assumption that the first layer of the film is solid.

The attenuation of third sound on glass has been measured as a function of frequency at temperatures from 1.2K down to 0.7K and over a variety of film thicknesses. The same He_3 cryostat was used and a powder reservoir was included. The substrate was a 2 centimeter long and two centimeter in diameter glass tube with third sound generators and detectors evaporated concentrically to the axis of the cylinder. The third sound traveled in a closed bath transversing from the outside of the cylinder around the end and back along the inside. The measurements were made in two ways. For high frequencies, the exponential decay of a pulse was observed, and for low frequencies resonances were excited and the decay time was measured.

The results fell into two categories. For thick films of about five layers or more, the attenuation was proportional to frequency. For thin films the attenuation was also proportional to frequency, but it approached some finite value as the frequency was lowered.

In general, the observed attenuation is greater and of different frequency dependence than that predicted by two fluid hydrodynamics. However, the functional form of the attenuation in the thicker films is well predicted by an uncertainty principle theory, although the calculated attenuation is an order magnitude larger than observed.

This is the doctoral research work of John H. Scholtz. See Technical Report #37 and publication #36.

38. A Study of the Trapping of Superfluid Persistent Currents in Superleaks

Persistent currents in superleaks in contact with bulk superfluid helium have been investigated using doppler shifts of the acoustic modes of an annular resonator partially packed with superleak, and with a simple gyroscopic technique. In an annulus in which the bottom fraction is packed with fine powder and the upper part is left unpacked, there are two hybrid acoustic modes consisting of a combination of the three bulk sounds of superfluid helium, first, second and fourth sound. One mode, with velocity C_{II}, consists of second sound modified by the presence of the superleak. The other mode, with velocity C_{14}, is an interpolated first and fourth sound mode. The two modes have been studied between the temperatures 1.2°K and the lambda temperature for annuli 20, 40, 60 and 80 percent filled with superleak. The velocities obtained were compared with the predictions of the two fluid hydrodynamic theory and good agreement was found. Some observed discrepancies are discussed in terms of depression of the superfluid fraction in the superleak due to size effects and dispersion of sound in a tube by wall attenuation.

The doppler shifts of C_{II} and C_{14} were used to obtain the persistent current velocities in the unpacked or free section and the packed region of the resonator. It is found that the persistent current velocity in the powder is about the same as is found in a fully packed annulus. In the free section some broadening of the C_{II}

resonances suggests a persistent current velocity of about 0.7 cm/sec in an 80% packed annulus with a 1 mm deep free section. Some possible alternate explanations for the broadening are discussed and it is concluded that the effect is principally due to doppler shift.

The decay of the observed persistent currents was observed for various initial velocities. Low velocity currents in the 80% filled annulus were observed not to decay in a 10 hour period. Larger velocity currents did exhibit some decay. In the 80% packed annulus the decay was about 5% per decade of time.

These observations are discussed in terms of the vortex configurations in the annulus. Vortices form a sheath or cage on the surface of the superleak and prevent loss of angular momentum from the persistent current in the superleak. The arguments are extended to the case of a superleak without walls - a bare superleak - and it is shown that in this case the vortices close on themselves forming a cage to contain the current.

Observations were made on a bare superleak using a simple gyroscopic apparatus suspended from a torsion wire. When the superleak is tilted with a persistent current, the change in the angular momentum vector leads to a torque which causes the gyroscope to swing on the torsion wire. In the experiment, the superleak was tilted at the resonant frequency of the torsion suspension and the amplitude of the swing was observed as a function of temperature with and without a current. The temperature dependence and absolute magnitude of the current in the bare superleak was found to be approximately the same as that observed in other experiments on a superleak completely enclosed by metal walls.

This is the doctoral research work of Joseph E. Heiserman. See Technical Report #38 and publication #'s 37, 40 and 42.

39. Non-Linear, Parametric Generation of Sound by Resonant Mode Conversion

When non-linear terms are included in the two fluid hydrodynamic description of superfluid helium-4, first sound (pressure-density waves) and second sound (temperature-entropy waves) are coupled. The interaction of two second sound waves to produce a propagating first sound wave is shown to occur at a specific angle which makes the point of intersection of the second sound waves travel at the speed of first sound. The growth of the mode converted first sound wave is calculated with and without attenuation of the primary (second sound) waves from 1.2°K to 2.15°K and from saturated vapor pressure to twenty atmospheres.

An experiment to observe this mode conversion process in a waveguide of rectangular cross-section is described. In the waveguide the intersection angle of the second sound waves is controlled by the ratio of the frequency of the higher order propagating mode of second sound to the cut-off frequency for that mode. Experimental measurements show that the resonant conversion of second sound to first sound in the waveguide occurs at the theoretically predicted frequency to within experimental error (0.1% to 0.2%) between 1.14°K and 2.04°K at saturated vapor pressure. The amplitude of the mode converted first sound is found to exhibit a quadratic dependence on the amplitude of the primary wave which is characteristic of a second order effect over the same range of temperatures. The quadratic dependence was observed over as much as 1.3 decades in primary wave power at a given temperature. A new application of the reciprocity calibration technique to a plane wave resonator geometry allowed an absolute calibration of the pressure microphones in situ. Absolute measurements of the coupling of the first sound generated by the resonant mode conversion process to the second sound agreed with theory to within 16% between 1.26°K and 1.41°K. The agreement between measured and theoretical values is a direct confirmation of the importance of the additional, intrinsically non-linear, Galilean invariant variable, $(\vec{v}_n-\vec{v}_s)^2$, in the thermohydrodynamics of superfluid helium. These results confirm the validity of the two fluid hydrodynamic description of He II up to terms of second order through the observation of a new non-linear acoustical interaction in fluids.

The theoretical formalism developed for the study of the mode conversion process is applied to the parametric amplification of second sound by high intensity first sound and the results are in disagreement with a previous calculation by Khokhlov and Pushkina. Using existing thermodynamic data, it is shown that the amplification process will give less than unity gain for first sound (pump) intensities which are below the cavitation threshold at saturated vapor pressure.

This is the doctoral research work of Steven L. Garrett. See Technical Report #39 and publication #'s 48, 55 and 56.

40. A Study of Persistent Currents in Superfluid ^{4}He

Decay of persistent currents in superleaks in contact with bulk superfluid helium has been studied using doppler shifts of the acoustic modes of an annular resonator partially packed with superleak. The two acoustic modes are an interpolated first-fourth sound and a modified second sound. They have proven to be a useful means of measuring persistent currents in both the packed and unpacked regions of the waveguide. Decay of such currents have been measured at 1.35°K for annuli 10, 20, 40, 60, 80, 90, 95 and 100 percent filled with superleak. The main result, which is somewhat surprising, is that the saturated persistent current and its fractional decay rate varies only slightly with superleak depth. This means that the stability of the current in powder is neither affected by the free exchange of mass between the two regions nor is it a strong function of the magnitude of the depth of the powder. Starting from 100% packing the fractional decay rate is about 2% per decade and increases to about 3% per decade at 10% packing. However, there exists a local maximum in decay rate at 90% packing.

Another phenomenon which was also studied is the doppler shift of gravity waves in a partially packed annulus, in relation to its possible application in the detection of persistent currents. The velocity of the gravity wave is about three orders of magnitude smaller than the fourth sound velocity in a similar geometry. Thus it seemed appropriate to use its doppler shift for measuring small persistent currents which could not be measured by the doppler shift of first-fourth sound. Having this is mind the necessary apparatus was built and subsequently a theoretical study of the problem showed that the doppler shift of gravity waves in the presence of a persistent current in superleak is weighted down by $(C_g/C_4)^2 \sim 10^{-6}$, which is very small and negligible. However the waves are still doppler shifted by a current in the unpacked region. Experiments were performed to detect the doppler shift of these waves and at the same time to establish the existence of a persistent current in powder after the apparatus was rotated above T_λ and brought to rest at the desired temperature (1.3°K). Measurements show that in spite of the fact that a current is present in the powder, gravity waves are not doppler-shifted. Some splitting of the fundamental mode is detected which corresponds to velocities $\sim$.8cm/sec. This splitting can indicate the existence of a current in the free region. Finally a decrease of the quality factor, Q, is observed after rotation.

This is the doctoral research work of Roset Khosropour Talaghany. See Technical Report #40 and publication #75.

41. Superfluid Helmholtz Resonators

We were the first to show that the master equation for a superfluid Helmholtz resonator is $\omega^2 = u_n{}^2 A/LV$, where ω is the angular-resonant frequency, u_n is alternately the velocity of first, second, and fourth sound. A is the cross-sectional area of the neck of length L, and V is the volume of the resonator. The fourth-sound resonance occurs when the resonator is packed with a porous medium which locks the normal fluid component. Experimental results on such a resonator are in agreement with this result. This is also a first. See publication #1.

42. Theoretical Work on Fluctuations and the Onset of Superfluidity

Professor Revzen of the Israel Institute of Technology in Haifa was a Visiting Professor of Physics and received partial support from the contract. In publications 7, 8 and 11 he developed a theory for the Onset of Superfluidity in Thin Helium Films which came very close to explaining our third sound results for superfluid onset. The accepted theory now is the Kosterlitz-Thouless theory of two dimensional liquids and our third sound results are in agreement with that theoretical result.

43. Macroscopic Quantum Uncertainty Principle

This was a speculative proposal of a way to understand anomalous third sound attenuation in terms of zero point fluctuations of the thickness of superfluid helium films. It is the non-linear interactions of these quantum fluctuations with the third sound wave which gives the anomalous attenuation. The paper was controversial and it received a generally adverse reception, although many highly respected physicists viewed it favorably. We continue to feel that there is merit in the speculation. See Publications 26 and 34.

44. Acoustic Resonance Effects in the Richards-Anderson Experiment on the Josephson Effect in Superfluid Helium

For a period of about 7 years (1965-72) it was believed that certain experiments in superfluid helium displayed the Josephson effect and yielded measurements of $^h/_m$. At an evening symposium at LT 13 at Boulder, Colorado attended by several hundred people the active experimenters in this field compared experiences with the result that the general consensus was that the phenomena were spurious and probably due to the ultrasonic fields which were necessary for the experiment. Publication 35 is a theory on how this Acoustic Effect comes about.

45. Determination of the Thermodynamics of He II from Sound Velocity Data

In 1974 we conceived of the idea of determining the thermodynamics of He II by measuring the velocity of 1st, 2nd and 4th sound and of the idea of constructing identical resonators for the three sounds machined out of a single cylinder of brass so that identical pressures and temperatures are insured. Dr. Hulin was a post-doc and he, aided by Joseph Heiserman constructed and tested the apparatus. Dr. Maynard followed Hulin as a post-doc on the contract and he, aided by Heiserman made the measurements. They covered the range from 1.2K to T_λ and from vapor pressure to the melting curve. The project was remarkably successful and tody the accepted standard tables in the temperature and pressure range mentioned are those contained in Publication 46. Publications 43 and 45 should also be consulted.

46. The Transition to Superfluidity in 2-dimensional He Films

In Publication 53 it is shown that the 3rd sound results of Publications 4, 15, 20, and 36 on the onset of superfluidity are in agreement with the Kosterlitz-Thouless result that the ratio of the critical superfluid area density divided by the critical temperature is $(\frac{2}{\pi})(\frac{m}{h})^2 k_b$. This was the first confirmation of this important result and we had the satisfaction of using our results which had been in the literature for 9 years for this purpose.

47. Fifth Sound

The sound wave which propagates in He II with the body conditions that the normal fluid is locked and there are no pressure swings is known as fifth sound. We had discussed its existance as early as 1963. A more exact discussion is given in Publication 61. Experimental evidence for this wave is given in Publication 62 and 65 and data on an experiment below 1°K is given in Publication 67.

48. Esoteric Sound Modes in He II

In planning experiments to demonstrate the existence of fifth sound it became necessary to examine the kinds of waves which propagate in systems where one or both of the necessary conditions, namely (1) normal fluid component is locked and (2) no pressure swings, exist. A galaxy of modes exist. These are described in Publications 57, 60, 63, 66 and 68.

49. The Velocity of 2nd Sound Near T_λ

The results of second sound velocity measurements made in the range 7 microkelvin to 10 millikelvin from T_λ are shown to be in excellent agreement with the hydrodynamic value contrary to previous measurements from other laboratories. Condenser transducers with superleak diaphragms which we developed were used here.

50. Zero Sound and the Viscoelasticity of Liquid ^{3}He

It is shown that Zero Sound (both longitudinal and transverse) is nothing more nor less than the elastic branch of viscoelastic sound. Simple acoustic dispersion and attenuation relations which apply for all values of $\omega\tau$ and which contain the zero-sound solution for $\omega\tau >> 1$ are obtained for liquid ^{3}He. They are found to agree extremely well with published results on longitudinal zero sound. A unique feature of a zero-sound experiment is that it yields all the information necessary to obtain the nonmagnetic and non-heat-conductive parameters of the normal ^{3}He as $T \to 0$.

51. Persistent Current Measurements in Superfluid Films

In Publication 74 we describe a current experiment. Using doppler shifted surface wave velocities we have measured the persistent currents in the films coating a rotating superleak and find the same kind of hysteresis curves found in filled pore superleaks indicating that this system also is analogous to a highly irreversible type II superconductor.

52. Subharmonics, Bifurcations and Chaos

There is a great deal of current interest in the vibrational response of systems to anharmonic excitation and of non-linear systems to harmonic or anharmonic drive. In such cases there is subharmonic response and through bifurcations period multiplication occurs as the amplitude of the drive is increased. We are using a shallow water gravity wave resonator which is oscillated vertically and have succeeded in seeing hosts of subharmonics. We also see the transition to weakly turbulent flow. This is described in Publication 77.

53. Miscellaneous Experimental Problems in the Acoustics of Classical Fluids

While the main thrust of our work is the study of superfluidity in quantum liquids we continue to have a strong interest in classical fluids. In Publication 14 we point out that by measuring the velocity of sound in pure ^{4}He gas and in a ^{4}He-^{3}He gas mixture it is possible to measure the isotopic ratio of the mixture extremely accurately. Subsequent unpublished measurements indicate that the atomic mass can be measured to a few parts per million. Publication 28 is an experimental study of the temperature dependance of an anisotropic mode in a nematic liquid crystal. In Publication 49 some unpublished results of an experiment done in the early 1950's are presented and shown to be in excellent agreement with the radiation pressure expression given by L.V. King. Publication 47 describes some work which was done at the Jet Propulsion Laboratory but with which I was associated. This is a striking effect in which the torques and spinning velocities are quite large. Publication 54 describes reciprocity calibration procedures which we found very important in our low temperature research.

Publication 64 describes a very nice theoretical and experimental study of the effect of surface tension on the propagation of shallow water gravity waves. For his part in this study David Heckerman was awarded the first Apker Award (outstanding graduating senior in Physics) of the American Physical Society.

54. Collective Modes in Superconductors

The macroscopic theory of superconductors was generalized to include irreversible and relaxation phenomena. In addition to unusual thermal conduction, charge fluctuation and contact potential modes, it was shown that a low frequency diffusive resistance mode becomes propagating at high frequency. Subsequent microscopic investigations of others have demonstrated the validity of this explanation of the Goldman modes. See Publication 53.

55. 1/f Noise

A divergent low frequency noise characterizes almost all measured power spectrums. It is well known that linear response theory cannot begin to account for this phenomenon. We have shown that non-linearities can mix down the high frequency noise (of which there is an unlimited amount) through difference processes and leads to a 1/f power spectrum. Though there is still no accepted explanation of 1/f noise we are convinced that our picture has the essential ingredients. Furthermore we have proposed many experiments on noise which should yield an insight into 1/f phenomena. See Publications 51, 52 and 70.

56. Off Equilibrium Light Scattering

We have shown how the Navier-Stokes equations with a small temperature gradient lead to unexpected singularities in the spectrum of light scattered at long wavelength. This has turned into an extremely hot field as these long wavelength divergences were not expected. Will the Navier-Stokes equations or the fluctuation-dissipation relations need to be modified at long wavelength where they were generally thought to be exact? See Publication 73.

57. Superfluid Hydrodynamics

A unified view of superfluid and superconducting phenomena was presented based upon the two fluid hydrodynamics. Phenomena included, thermal vortices, boundary conditions, shock waves and sound modes, rotating He II, stability conditions, transverse sound, vortex drag, thermal fluctuations and the condensed Bose gas. The general conclusion is that the two fluid hydrodynamics provides at least as good a description for liquid helium as does the Navier-Stokes equation for water. See Publication 59.

58. Vortex Transitions in 2 Dimensions

It was shown how phase transitions due to fluctuations in vorticity can be simply understood in terms of the Landau theory of elementary excitations. This approach made possible a calculation of effects due to finite size and currents. Some results on the critical field for superconducting films are first being observed in other laboratories. See Publication 77.

59. Non-Linear Hydrodynamics and Quantum Acoustics

Using the second law of thermodynamics as a guiding principle we have renormalized classical unquantized non-linear hydrodynamics so that non-linear processes do not remove energy from the zero temperature noise. In this way, non-linear scattering can be used to yield all of the essential results of the quantum theory of interacting phonons. We expect these considerations to be especially relevant to macroscopic quantum measuring devices.

60. Review Papers and Tutorials

Publications 17, 20, 23, 41, 70, and 73 are such papers.

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